Flexible Linearity Profile Amplifier For Software Defined Radio Applications

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ABSTRACT

A highly linear Low Noise Amplifier (LNA) using a flexible feedforward linearisation scheme is described. The wideband LNA is designed for use in the frequency spectrum between 1 and 2GHz. It has a tuneable linearity profile which allows it to be adjusted for wideband moderate linearity or narrowband high linearity.

The linearity can be tuned so a wideband Third Order Intercept Point (IP3) improvement of 4dB can be achieved from 1.3 to 1.7GHz or a narrowband (1MHz) 13dB improvement can be realised anywhere between 1.1 and 1.7GHz

I. INTRODUCTION

The rapid growth of the communications industry has required the rapid introduction of new standards to cater for the increase in capacity. This posses a problem for hardware manufacturers who have to build multiple transceivers for all the different standards. One solution to the multiple transceiver problem is the Software Defined Radio (SDR) [1] which can be used with any of the available standards simply by downloading software to configure its flexible hardware.

Current mass-market personal mobile communications standards in Europe included GSM between 880 and 960MHz and DCS1800 between 1710 and 1880MHz, both using GMSK. This is expanded in America with TDMA and CDMA between 820 and 900MHz using forms QPSK modulation. Japan again has its own standard using different frequencies and modulations schemes.

Great flexibility is required to cater for future standards; mobile communications (3G at 2.3GHz) and network standard (Bluetooth at 2.45GHz and HyperLan at 5.4 and 5.85GHz). These involve an extended bandwidth up to 5.85GHz, complex modulation schemes like OFDM (Orthogonal Frequency division Modulation) and wide bandwidths of 20MHz.

Current wide bandwidth components are available from a number of manufacturers offering moderate dynamic range. To improve the upper end of the dynamic range the intercept points of the amplifier can be increased using a linearisation scheme. Linearisation schemes are commonly applied to Power Amplifiers (PA) in transmitters to reduce the Adjacent Channel Power (ACP) caused by Intermodulation Distortion (IMD). It is only recently that they have been applied to the receiver LNA to cope with a large dynamic range of signals. Examples of this can be found in [2] and [3]. Reference [2] discusses both narrowband high linearity and octave bandwidth moderate linearity feedforward amplifiers whilst [3] discusses a narrowband feedforward amplifier designed for use in a TDMA/CDMA basestation.

II. SOFTWARE DEFINED RADIO ENVIROMENT

The SDR environment is a large region of the radio spectrum, typically between 400MHz and 6GHz. Within this spectrum there are multiple interferes which could generate IMD products that may corrupt with a low power received communication signal. The extent of in-band interfering signals were investigated in a trial as described in [4]. The worst case results of this trial are shown in Figure 1.

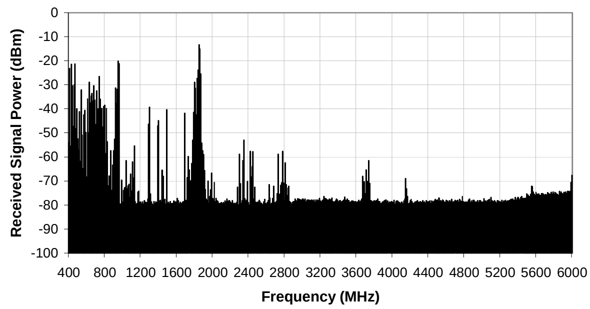

Figure 1: SDR Trial Worst Case Result

From Figure 1, it is clear that the largest in-band signal (-13dBm) originates from a DCS1800 basestation at 1850MHz. Using this as the maximum in-band signal and the DCS1800 required received sensitivity of -102dBm the input IP3 of the amplifier is calculated at 37dBm in order to maintain the 10dB carrier-to-cochannel ratio of GSM.

In the channel shown in Figure 1 the majority of the interfering signals are grouped together in certain bands, whilst there are large regions of the spectrum containing little energy. This allows the use of a selective linearity profile with a peak centred around the bands containing the large signals instead of a wideband linearity profile. If the power profile of the channel is already known then the LNA can have its linearity profile tuned to suit this. The power profile of the channel can be measured with a simple spectrum analyser similar to that used for the SDR trial. This gives a direct indication of the relative power of the signals in the channel and, more importantly, their frequency.

III. FEEDFORWARD AMPLIFIER CHARACTERISTICS

To meet the linearity requirements of the SDR environment receiver front-end linearisation will be required. Most linearisation schemes have been designed with PAs in mind where the characteristics of the input signal are already known and operate over a relatively narrow bandwidth. Of the various linearisation schemes available only feedforward is applicable for use in an LNA as described in [2] and [3]. A recent novel technique developed by one of the authors [5] also shows promise of providing an alternative wideband linearisation technique. It utilises the signals seen at the input of an amplifier as the error signal which is phase controlled and subtracted from the output. A simplified diagram of the feedforward structure is shown in figure 2.

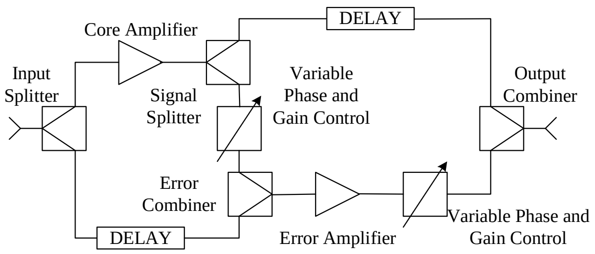

Figure 2: Feedforward Amplifier Block Diagram

For IMD suppression the two Variable Phase and Gain Control elements have to be carefully adjusted so that the input signal is suppressed from the output of the Error Combiner. The Output Combiner will then cancel the IMD without any cancellation of the wanted signal. Special considerations need to be given to the splitter and combiner following the Core Amplifier since their insertion loss reduces the IP3 of the total amplifier. For this system the Signal Splitter and Output Combiner have a combined insertion loss of 4.5dB so the total amplifier must offer an IMD suppression of 9dB before it can start to show any improvement over the Core Amplifier.

C. Amplifier Specifications

To ensure good IMD suppression the phase and gain errors in the two loops need to be minimised. To operate over a wide bandwidth this requires amplifiers with flat gain (and linear phase) characteristics. For this application Mini-Circuits [6] ERA-5 and ERA-6 were chosen as they provide a good combination of gain, IP3, linear phase and gain flatness. An ERA-5 followed by an ERA-6 was chosen for the Core Amplifier since this provided a gain of at least 25dB over range 1 to 2GHz and combined input IP3 of 14dBm. With the excess loss in the various combiners the gain is reduced to 18dB and input IP3 increased to 17dBm. Over the 1 to 2GHz band, gain and phase flatness were to within 3dB and 10° respectively.

It is often the case that the Error Amplifier requires more gain due to the extra loss incurred in the Error Combiner, so for this two ERA-5 amplifiers were chosen which have a higher gain than the ERA-6, but slightly lower IP3.

B. Variable Phase and Gain Control

Various techniques were examined to find suitable electronically controllable phase and gain elements which have flat phase and gain responses. The final solutions are based on 90° hybrid combiner and integrated into a single unit. These have the advantage of providing an overall 180° phase shift so the Error Combiner can be a 0° Wilkinson type.

C. Splitters and Combiners

With the exception of the Signal Splitter all of the splitters and combiners are based on wideband Wilkinson power splitters. The Signal Splitter is a T-network attenuator designed so that the main output only experiences 1dB loss whilst the other output which drives the Variable Phase and Gain Control experiences 20dB loss. This ensures that the IP3 of the Core Amplifier is not severely reduced whilst attenuating the error output to a level similar to that of the input for the Error Combiner.

IV. FLEXIBLE LINEARITY PROFILE FEEDFORWARD AMPLIFIER

A. Wideband Response

Although the feedforward amplifier is capable of wideband IMD suppression this is only possible where the gain and phase response of all of the components is very flat in the frequency domain. Often this is not possible and feedforward amplifiers are currently only used for narrowband applications. As a test of wideband performance the amplifier was set-up for a trade-off between wide bandwidth and IP3 improvement.

It was possible to calibrate for a wideband 20dB suppression in the first loop and 15dB in the second loop. The first loop is that which incorporates the Core Amplifier, whilst the second loop is that incorporating the Error Amplifier. This gave an IP3 improvement of approximately 4dB more than the Core Amplifier over a 250MHz bandwidth centred around 1.46GHz. A graph of the IP3 improvement is shown in Figure 3.

It is clear that wideband IP3 improvements are hard to achieve, mainly due to matching the phase and gain balances over a wide bandwidth. As a result, a means of tuning the linearity profile was investigated since it was noted that very large IMD suppression could be achieved at narrow bandwidths over which the phase and gain were reasonably flat.

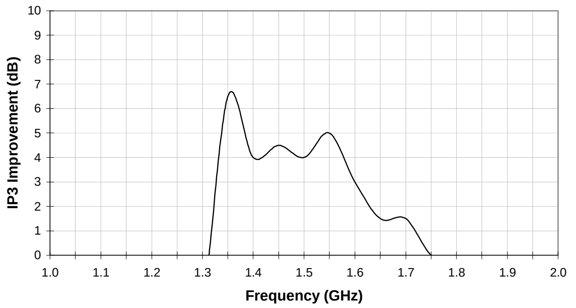

Figure 3: Wideband IP3 Improvement

B. Narrowband Tuneable Response

The addition of the electronically Variable Phase and Gain Control elements made tuning comparatively easy. Using the configuration described above it was possible to tune the linearity peak between 1.1 and 1.7GHz. Figures 4 and 5 show the narrowband signal suppression for the first and second loops respectively, at various centre frequencies.

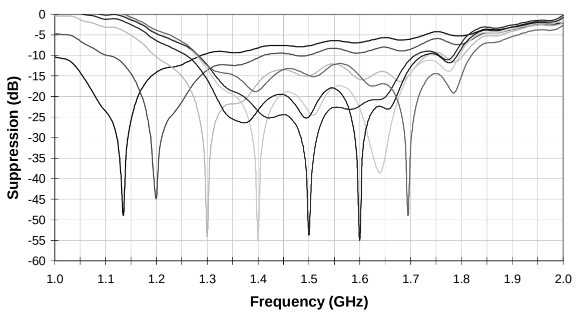

Figure 4: First Loop Tuneable Suppression

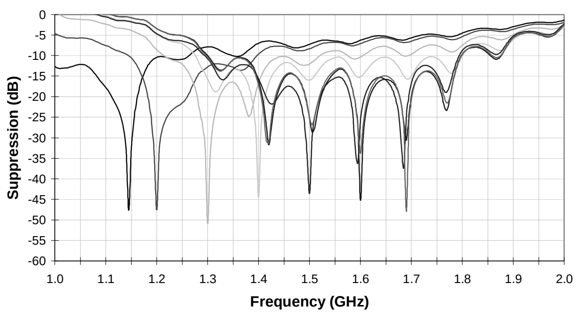

Figure 5: Second Loop Tuneable Suppression

It is seen that very large suppression can be achieved when correctly calibrated, typically -50dB in the first loop and -45dB in the second. Analysis has shown that the IP3 improvement is very closely related to the second loop suppression. This is approximately half the suppression minus the output combiner/splitter loss.
The actual IP3 improvement is more complicated to calculated because of the signal bandwidth involved. The bandwidth suppression of the first loop must be great enough to cover the wanted signal, whereas in the second loop the suppression bandwidth needs to also cover the IMD products. This means the second loop suppression bandwidth must be three times that of the first loop suppression bandwidth for third order spurious suppress.
The individual suppression graphs (Figures 4 and 5) indicate that IMD suppressions of 20 to 25dB should be achieved by the feedforward amplifier. The feedforward amplifier was tested using a two-tone test with a frequency separation of 1MHz. Below in Figures 5 and 6 is shown the spectral output from the Error Combiner and without the suppression applied, at a centre frequency of 1.4GHz.

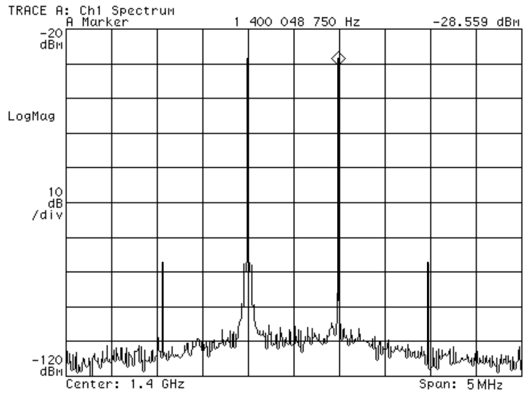

Figure 6: Output of Error Combiner with Suppression Removed

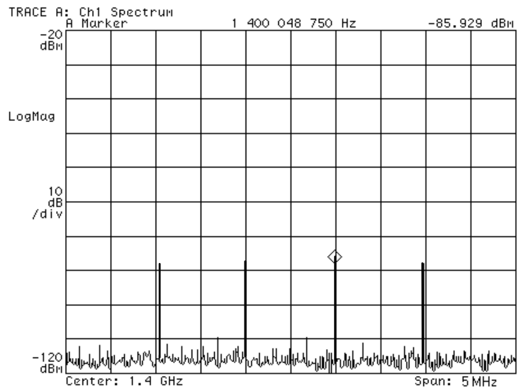

Figure 7: Output of Error Combiner with Suppression Applied

A fundamental suppression of 57dB is possible without attenuating the IMD products. This exceeds the suppression achieved in Figure 4.
Based on these promising results the rest of the amplifier was tested and the spectrum of the Output Combiner monitored on the spectrum analyser. Figures 8 and 9 show the output spectrum with the error amplifier switch off and then on respectively to indicate the amount of IMD suppression achievable.
When set-up correctly, switching the Error Amplifier on and hence introducing the second loop has the effect of reducing the IMD by 36dB. When allowing for the output combiner and splitter the IP3 improvement is 13dB compared to the Core Amplifier. The result is to increase the input IP3 of the feedforward amplifier to 27dBm whilst still maintaining a gain of 15dB. The

gain is reduced by about 0.5dB by the introduction of the Error Amplifier into the second loop, an indication of non-perfect suppression in the second loop.

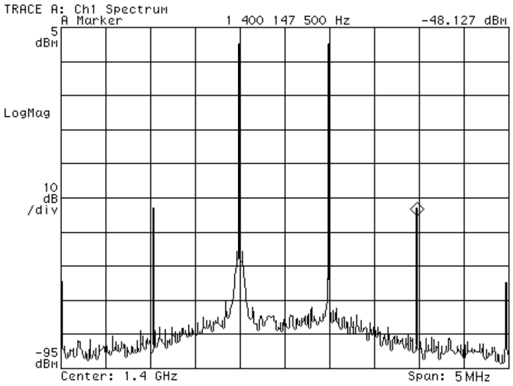

Figure 8: Error Amplifier Switched Off

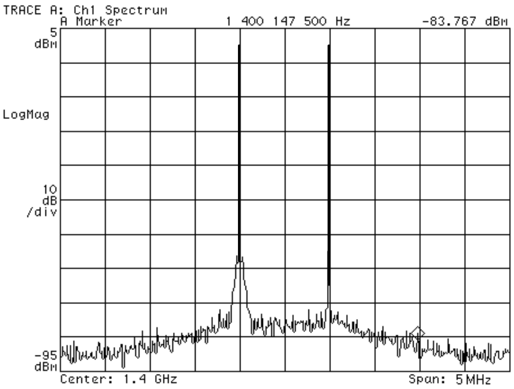

Figure 9: Error Amplifier Switched On

By adjusting the Variable Phase and Gain Control elements in each loop it was possible to tune this IP3 improvement over the 1.1 to 1.7GHz band. This is shown in Figure 10.

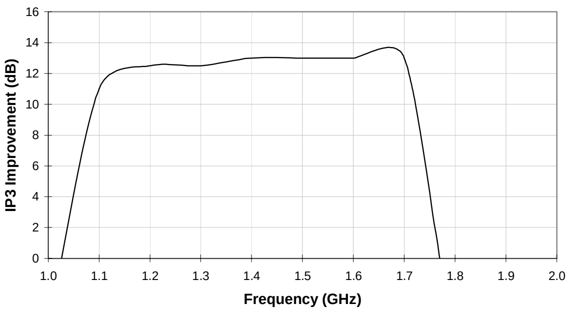

Figure 10: Tuneable Narrowband IP3 Improvement

As a test of bandwidth the feedforward amplifier was set to 1.4GHz as used in Figures 6 to 9 and the frequency spacing of the two tones adjusted to determine the roll-off of IP3 improvement with bandwidth. It would seem logical looking at Figures 4 and 5 that the smaller the frequency spacing of the two tones the greater the IMD suppression that can be achieved as the tones are allowed to slide down the steep sides of the suppression troughs. Due to the frequency resolution (5MHz) that was used when recording the loop suppressions it is not possible to examine the suppression at very close frequency spacing. If one of the troughs is zoomed into with a finer frequency resolution then a sharper trough would be visible. The channel spacing was varied between 1kHz and 100MHz to test the limits of the suppression. The results are graphically plotted in Figure 11.

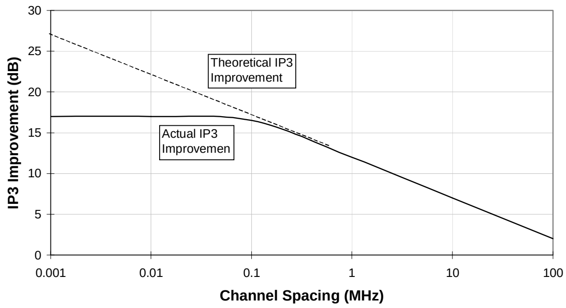

Figure 11: IP3 Improvement Against Channel Spacing

The practical results tail-off at close channel spacing and do not meet the predicted results. The reason for this is three fold; the dynamic range of the spectrum analyser used is limited to 95dB, signal leakage from the output of the Core Amplifier to the output of the Output Combiner and errors in the phase and gain matching.

First of all, the measurement of an IP3 improvement of 25dB requires a dynamic range of approximately 120dB, which is very difficult to achieve. Secondly, due to the extremely small power of leakage signals (~-80dBm) present at the output, it is difficult to shield the system against them completely. The phase and gain match needs to be very accurate to achieve deep suppression troughs.

Based on the theoretical results above it should be possible to meet the requirement of input IP3 for signal spacing of 20kHz. Signals this close together can not be effectively removed by the use of filters. A combination of filters and tuneable linearity profile amplifier maybe used to cope with all scenarios that an SDR is likely to experience.

One key note of interest is that when the amplifier is tuned across the two tones the IMD products do not reduce in harmony. For all the IP3 improvement bandwidth measurements the suppression troughs are tuned to between the two tones. If the trough is tuned to exactly the same frequency as one of the tones then its closet IMD products will be significantly suppressed whilst the other IMD product increases. This is an indication that only one of the tones needs to be effectively suppressed to reduce one of the IMD products. Typically another 5dB suppression of one of the IMD products can be achieved before it disappears into the noise floor of the spectrum analyser.

V. CONCLUSION

The feedforward amplifier here is capable of either wideband moderate linearity improvement or narrowband high linearity improvement. In addition the high linearity profile can be tuned over a large frequency range to provide a high dynamic range when and where it is required.

An IP3 improvement of 4dB over a 250MHz bandwidth can be achieved with a wideband suppression in each loop. Narrowband IP3 improvements of 13dBm can be used with upto 1MHz frequency separation of a two-tone test. This high linearity profile can be tuned between 1.1 and 1.7GHz.

The combination of IP3 improvement with the chosen Core Amplifier resulted in and a 1MHz bandwidth input IP3 of 27dBm which still does meet the 37.5dBm required by a true wideband SDR receiver based on current deployment standards.

It should be noted that under the conditions of this work the physical construction of the amplifier is important since even a tiny leakage can reduce the amount of IMD suppression of the amplifier significantly. The dynamic range demands of testing the feedforward amplifier are currently higher than that of the available test equipment, which does not allow large IMD suppression ratios to be measured. Finally it should be noted that the phase and gain balance within the two loops is critical and extremely difficult when trying to achieve a large IMD suppression ratio.

VI. ACKNOWLEDGEMENT

The authors would like to thank EPSRC for funding to pursue the research into feedforward receiver amplifiers.

VII. REFERENCES

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